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IMAGING COMET ISON C/2012 S1 IN THE INNER CORONA AT PERIHELION

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ABSTRACT

Much anticipation and speculation were building around comet ISON, or C/2012 S1, discovered on 2012 September 21 by the International Scientific Optical Network telescope in Russia, and bound for the Sun on 2013 November 28, with a closest heliocentric approach distance of 2.7 $R_\odot$. Here we present the first white light image of the comet's trail through the inner corona. The image was taken with a wide field Lyot-type coronagraph from the Mees Observatory on Haleakala at 19:12 UT, past its perihelion passage at 18:45 UT. The perfect match between the comet's trail captured in the inner corona and the trail that had persisted across the field of view of 2–6 $R_\odot$ of the *Solar and Heliospheric Observatory* Large Angle and Spectrometric Coronagraph Experiment/C2 coronagraph at 19:12 UT demonstrates that the comet survived its perihelion passage.

Key words: comets: general – comets: individual (C/2012 S1 ISON) – methods: observational – Sun: corona

1. INTRODUCTION

On 2011 December 16, comet C/2011 W3 Lovejoy made a spectacular entry into and exit from the corona at a perihelion heliocentric distance of 1.2 $R_\odot$. Its striking footprints were captured in the extreme-ultraviolet (EUV) emission (Bryans & Pesnell 2012; McCauley et al. 2013) by a number of space-based telescopes, most notably by the very high (1″.5) resolution Atmospheric Imaging Assembly (AIA) instrument on the *Solar Dynamic Observatory* (*SDO*; Lemen et al. 2012). These footprints were manifested as striations produced by the enhancement of the EUV emission from Fe ions, especially from the Fe x 17.1 nm line, along different magnetic field lines as the comet's path intercepted them (see Figure 1 in Bryans & Pesnell 2012 for pre-perihelion, and Figure 1 in McCauley et al. 2013 for post-perihelion). Given our current knowledge of the composition of comets (A'Hearn et al. 2012), in particular with information that emerged from the *Deep Impact* encounter with Comet 9P/Tempel 1 (Feldman et al. 2006; Schulz et al. 2006), such enhancements can be accounted for by charge exchange processes between highly ionized coronal material and molecules evaporating from the comet's nucleus in the corona, such as CO, H_2O, and hydrocarbons. Charge exchange processes not only ionize the highly excited radicals from the evanescent cometary material, but simultaneously decrease the charge state of coronal ions while increasing their excitation level. Thus the interaction of sublimating cometary material with the coronal plasma can lead to enhanced EUV emission as captured by AIA. (An alternative explanation based on the ionization, sublimation, and photodissociation of cometary material can be found in Sekanina & Chodas 2012, Bryans & Pesnell 2012, and McCauley et al. 2013).

Comet ISON, or C/2012 S1, discovered on 2012 September 21 by the International Scientific Optical Network telescope in Russia (Nevski et al. 2012), was bound for the Sun on 2013 November 28, with a predicted perihelion distance of 2.7 $R_\odot$. Ground and space observations of the comet prior to its solar encounter, as summarized by Meech et al. (2013), predicted that comet ISON was as likely as comet Lovejoy to have an equally spectacular entry into the corona. Furthermore, its survival was more likely, given that its perihelion distance was farther away from the Sun. Consequently, high hopes were building up for a repeat performance by comet ISON on 2013 November 28 at 18:45 UT.

Although ISON's perihelion distance was at 2.7 $R_\odot$, its projected closest approach point in the plane of the sky was 1.7 $R_\odot$. The white light observations from the Large Angle and Spectrometric Coronagraph Experiment (LASCO)/C2 and C3 coronagraphs on the *Solar and Heliospheric Observatory* (*SOHO*; Brueckner et al. 1995), which continuously observe the corona, would automatically capture the comet, albeit only down to the edge of the innermost occulter, namely, at 2 $R_\odot$ for LASCO/C2. Hence, the comet would disappear behind the LASCO/C2 occulter around perihelion. At that time, the comet would be barely visible at the edge of the occulters of the COR2-A and COR2-B coronagraphs of the twin Solar TErrestrial RElations Observations spacecraft, STEREO-A and STEREO-B (Howard et al. 2008), stationed at 150° from Earth, and would traverse the field of view of the COR1 coronagraphs, although the latter are difficult to calibrate (Knight & Battams 2014). To capture the comet's entry into the inner corona at perihelion, space-based EUV observations with AIA/*SDO* would only be possible by off-pointing the telescope to four positions along the comet's anticipated trajectory, so that its field of view of $41' \times 41'$ could intercept its path.

The timing of the perihelion passage at 18:45 UT was such that ground-based observations in the visible could be made from Hawaii, and would fill the inevitable white light observing gap of LASCO/C2 below 2 $R_\odot$. In this Letter we report on the first, and possibly only, white light image of comet ISON taken during perihelion passage with a wide field of view coronagraph.

2. OBSERVATIONS

The projected closest approach point in the plane of the sky, 1.7 $R_\odot$ at perihelion, necessitated the use of a coronagraph for observations in the visible wavelength range. Our team mounted two sets of telescopes on the spar at the Mees solar observatory on the summit of Haleakala. These consisted of a wide-field

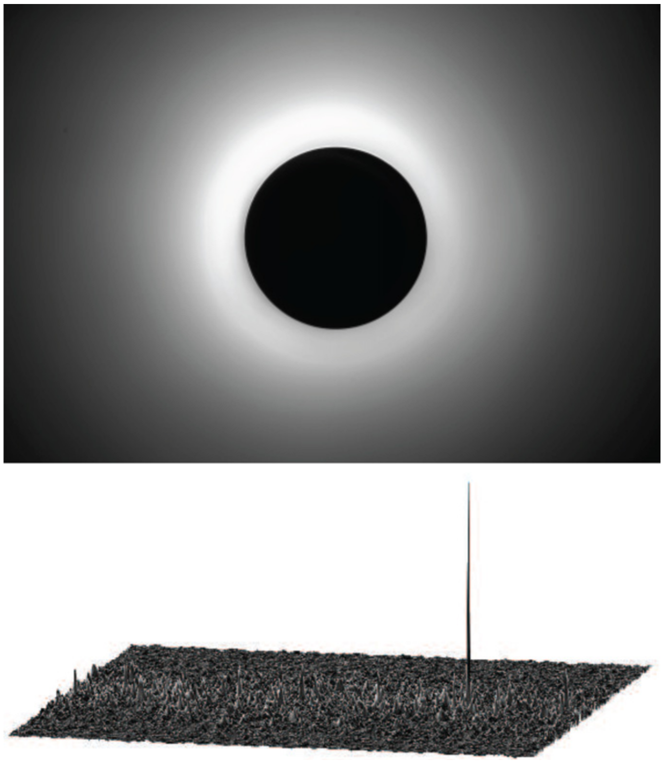

Figure 1. Top: white light image taken on 2013 November 28 at 19:12 UT with a newly designed coronagraph. The field of view was 2°.1 × 1°.4 and the effective angular size of the occulter was 36′. Bottom: two-dimensional phase correlation pattern. The *x*-axis (long dimension) corresponds to rotation, and the *y*-axis to the scaling factor. The brightest peak corresponds to a 5σ level at the location where the scaling factor is 1.012 and the rotation 33°.75. (See Druckmüller 2009 for more technical details.)

white light Lyot-type coronagraph (Lyot 1939), and a pair of ATIK cameras retrofitted with narrow (0.5 nm) bandpass filters centered on the Fe xi 789.2 nm line and the neighboring continuum at 788.1 nm (a system successfully tested with total solar eclipse observations; Habbal et al. 2011), with external occulters placed 150 inches away from the optics at the tip of the spar. In addition, the sky near the Sun was scanned in search of ISON using an imaging high-resolution spectrometer equipped with a linear occulter. We report here on the white light observations only, as the data through the narrow bandpass filters and the spectrometer are still being analyzed.

Weather conditions were not ideal, with passing clouds just before and right up to perihelion. The best observing opportunity presented itself immediately past the closest approach point. To accommodate the wide field needed for the comet flyby, we used a full frame (24 × 36 mm chip size) DSLR Nikon D800E camera with 36 megapixels. The telescope consisted of an 88 mm diameter apochromatic lens, with a 498 mm focal length at F/5.6 and a 2″ field flattener. This telescope was retrofitted with a classical Lyot coronagraph design, namely, an occulting disc with a field lens, a Lyot stop with a variable iris, and a second objective lens. A commercially available "prominence observing unit" from W. Lille was adapted to match the short focal length of the main optics. The white light image shown in Figure 1 (top) was taken at 19:12 UT in a single frame with an exposure time of 1/8000 s, ISO set at 50, and software binning at 8 × 8 pixels.

To relate this image to the *SOHO* LASCO/C2 coronagraph image, where the trail of the comet had been clearly visible throughout the coronagraph's field of view and up to its edge

Figure 2. Composite of our processed white light image (inner inset), and the LASCO/C2 image at 19:12 UT during perihelion passage. The extension of the dust trail of the comet in the LASCO/C2 field of view is clearly visible in the inner corona (inner inset). Note the presence of a thin tail visible more than halfway through the LASCO/C2 field of view. Its angular separation from the dust tail was too small close to the edge of the occulter, and could be the reason why it was not captured in the inner corona.

at 2 $R_\odot$ (Figure 2), our white light image was rescaled to match the size of the LASCO/C2 image. The rescaling factor was computed from the parameters of our optical system and the angular diameter of the Sun. The two images were then aligned using the phase correlation method developed by Druckmüller (2009), which yields the shift between the two images, the scaling factor and rotation. The reliability of these latter parameters can be expressed by a correlation peak height relative to the standard noise deviation (σ) in the resulting phase correlation image (Figure 1, bottom). We obtained a value of 1.012 for the magnification, confirming that the scales of the LASCO/C2 image and our coronagraph are identical within 1%. The 5.1σ height of the correlation peak value practically excluded the possibility of random alignment. The calculated rotation was 33°.75, which was very close to the value expected from the orientation of the coronagraph. Because of reflections in the optical system and the diffraction patterns caused by the iris and occulter of the coronagraph, correlation-based alignment of the two images was the only reliable approach; attempting to align solar features could have easily led to misinterpretations.

The composite from the co-aligned white light LASCO/C2 and our image at 19:12 UT is shown in Figure 2. Our image was processed with a radial Gaussian mask, in order to decrease the extreme radial gradient of the brightness to bring out coronal features, which at the same time enhanced the comet's trail. The correspondence between the trail of the comet in the two is almost seamless. Another proof of the accurate alignment of the two images is the excellent correspondence between several coronal features, mainly streamers, between the two.

Unfortunately, the comet's trail was not detected with our coronagraph past-perihelion later on, most likely due to the presence of high cirrus clouds. Other reasons could be due

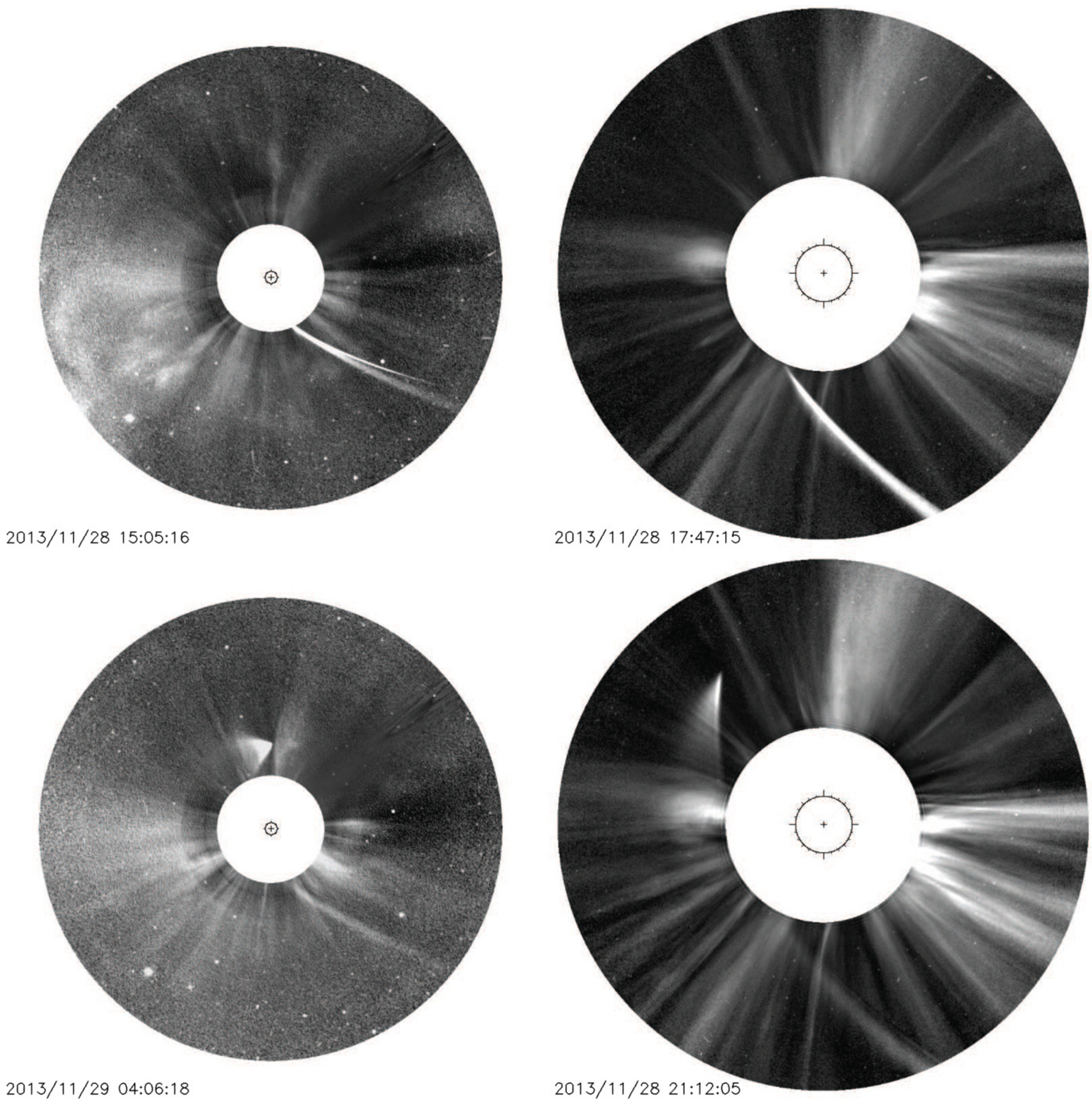

Figure 3. Selection of LASCO/C2 and C3 images taken (clockwise) on 2013 November 28 15:06:11 UT (C3), 17:48:08 UT (C2), 21:13:08 UT (C2), and on November 29 at 04:07:41 UT (C3). The images have been processed with the technique developed by Morgan et al. (2006). The inner dashed circles correspond to the size of the solar disk. Note the presence of a sharply defined (most likely Na) tail at 15:05 UT, starting around 20 $R_\odot$ in the LASCO/C3 field of view (top left). It is likely that this tail formed the inner, sunfacing, sharp boundary of the comet's fan-shaped "halo" past-perihelion.

to the evaporation or dispersion of a significant amount of cometary material, including dust, thus reducing the intensity of the scattered emission to values much lower than the coronal intensity. The increase in sky brightness to a level exceeding the coronal and cometary emission past-perihelion could have also contributed to the lack of detection of a very faint signal.

Prior to perihelion, the full trail of the comet had persisted throughout the fields of view of the LASCO/C3 and C2 coronagraphs (Figure 3, top panels), up to the edge of their respective occulters. As the comet emerged post-perihelion in the LASCO/C2 field of view, its trail had changed into a fan shape, with a sharp edge on the sunward side, as shown at 21:13:08 UT in Figure 3. The angular extent of the fan increased with distance, as seen within the LASCO/C3 field of view, shown in Figure 3 at 04:06:18 UT on November 29. Interestingly, the comet's trail from its pre-perihelion passage was still visible in the LASCO/C2 image at that time. The fan-shaped trail was still visible on 2013 November 30 at 13:39:54 UT when it exited the LASCO/C3 field of view.

The white light emission from the comet in the LASCO/C2 field of view prior to perihelion was most likely a reflection of the classical cometary dust tail. (A more detailed account of the LASCO/C2, *STEREO*/COR2-A, and *STEREO*/COR2-B observations was submitted independently by Knight & Battams 2014 at the same time as this work.) In addition, a very thin curved tail was captured in both the LASCO/C3 and then LASCO/C2 fields of view prior to perihelion. It is very likely that the sharp inner edge of the comet's trail post-perihelion coincided with this tail, while the dust tail produced the fan shape. Our interpretation is that the sharp tail was produced by the fluorescent excitation of atoms—probably Na—outgassing from the larger particles broken off from the comet's main body. On the other hand, the broad trail moving away from the comet's orbit most likely consisted of atoms, molecules, and very fine dust particles pushed away by the Sun's radiation pressure. As a consequence of (the simplest assumption of) spherical expansion, the density of the outgassing atoms around these large fragments would decrease very sharply with distance from their host fragment, thus leaving behind the observed sharp trail. Radiation pressure is probably too weak to push the larger fragments away from their original location where they were produced along the comet's trajectory. The fact that this sharp trail was seen post-perihelion when seemingly only dust remained implies that large fragments were still present in the dust that had survived the perihelion passage. Such neutral Na atom tails had been observed in some comets, such as Hale–Bopp, albeit at 0.98 AU (Cremonese et al. 1997). The Na D doublet line emission was also detected in the spectra of ISON taken shortly after perihelion during this observing campaign (A. Ding et al., in preparation).

3. DISCUSSION AND CONCLUSION

As noted earlier, AIA/*SDO* was off-pointed to four positions along the comet's anticipated trajectory during perihelion passage, in the hope of capturing the footprints of the comet in the instrument's field of view, as was achieved with comet C/2011 W3 Lovejoy. As comet ISON entered the field of view of the off-pointed AIA/*SDO*, no EUV emission was detected. The immediate conclusion was that the comet had faced its demise, an announcement that almost instantly made the rounds of the internet and the press (www.npr.org/blogs/thetwo/2013/12/03/248202813/comet-ison-is-no-more-nasa-says). (Ironically, no mention was made that this instrument had not detected any coronal emission either at that distance.) These announcements were rather surprising, given that the comet had still been visible throughout the field of view of LASCO/C2, until its disappearance behind the instrument's occulter at 2 $R_{\odot}$.

The absence of detectable EUV emission, despite a clear signal in white light emission, can be readily accounted for by considering its excitation process. The intensity of the EUV emission is proportional to the product of the ion and electron density along the line of sight; hence, it drops very steeply with radial distance from the Sun. In the example of comet Lovejoy, the observed EUV enhancements of the footprints of the comet, as it intercepted coronal structures, was mainly due to a localized enhancement of coronal density as a consequence of the interaction of sublimating cometary material with the coronal plasma. Consequently, in comparison, the EUV footprint emission of comet ISON at 2.7 $R_{\odot}$ would be considerably reduced compared to the distance at which comet Lovejoy had its closest approach point. Hence, the lack of EUV detection by *SDO* was a consequence of too weak an EUV signal along the comet's trajectory, because neither cometary footprint nor coronal emission were recorded at the comet's predicted position. Even if a significant increase in exposure time for the AIA detectors had been planned, it is doubtful that any detection of EUV emission from the comet's footprints through the corona, as well as from the background coronal emission, could have been achieved at that distance.

For comets in general, the white light emission is scattered photospheric radiation from the dust grains in the comet's coma and tail, in a way similar to the F-corona which is produced by scattering from interplanetary dust. The intensity of this emission is directly proportional to the density of the scatterers. The detection of the comet ISON's trail throughout the LASCO/C3, C2, and *STEREO*/COR2-A and COR2-B fields of view, and inner corona implies that the dust content was large enough for the resulting white light emission from the comet to be detected, and clearly distinct from the coronal electron-scattered component. However, a detailed study of the cometary white light emission, reported here, compared to the coronal emission, is needed before any quantitative remarks regarding the size of the nucleus and/or the dust grains that survived perihelion can be made.

In closing, we note that although comet ISON disappointed most observers because it did not meet the expectations of a behavior similar to that captured in the EUV with comet Lovejoy, the transformation of comet ISON's dust tail post-perihelion was quite spectacular in its own right. While comet Lovejoy disintegrated approximately 1.6 days after perihelion (Sekanina & Chodas 2012), the dust fan-shaped remnant of comet ISON was still visible almost two days after its perihelion passage. As a pristine comet from the Oort Cloud on its first solar encounter, comet ISON, at the end of the day, did put on a different, yet equally exciting show.

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